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RECOGNITION OF THREE DISTINCTIVE FEATURES IN BRIEF-DURATION COMPLEX NON-SPEECH SOUNDS

Eugene B. Silverman and James H. Howard, Jr.

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Three experiments investigated the effect of an interfering white noise on the recognition of brief-duration complex sounds. Listeners were presented with a 20 msec signal followed, after a variable delay, by a 500 msec white noise burst. Their task was to classify the signal into one of two categories on the basis of either its fundamental frequency, waveform or formant frequency. The main focus of the experiments was to investigate the relation between performance and the auditory features or cues present in the signal. Recognition performance improved with

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20. Abstract continued

increasing inter-stimulus intervals up to an asymptote at approximately 200 msec. This finding is consistent with earlier results in suggesting that brief-duration signals are retained for a short time in a precategorical sensory memory for further processing. In addition, the data revealed that asymptotic performance level was determined primarily by the distinctiveness or discriminability of the relevant auditory feature and by the amount of listener experience with the relevant feature. It was concluded that practiced listeners have an improved ability to selectively focus their attention on specific auditory cues in a complex aural display.

INTRODUCTION

Rarely do we take second notice of the multitude of meaningful non-speech sounds we are exposed to daily. As with other modalities, the perception of meaningful auditory stimuli requires little effort and continues rather "automatically." Although we are normally not aware of the ongoing processes responsible for auditory perception, much empirical evidence indicates that substantial perceptual processing is required to recognize even the simplest auditory signal (e.g., Wightman & Green, 1974).

Although we can readily identify a variety of sounds, there are large differences in the relative difficulty with which particular sounds may be classified. The reasons for this can be revealed through an analysis of the psychophysical structure of the sounds and of the perceptual processes required to experience them. For instance, when classifying automobile and jet-turbine sounds, the differences between the physical structure of the two categories might be more apparent than the physical distinctions among different sounds within each set. These physical distinctions influence the perceptual processes applied to the sounds, leading to differences in perceptual complexity. In general, the greater the number of physical components that various sounds have in common, the more difficult it will be to distinguish one from another psychologically.

The psychological literature indicates a tendency for listeners to exhibit selective sensitivity to particular auditory dimensions or features. The present report describes three experiments that further investigate this phenomenon by requiring listeners to identify the perceived quality (high pitch or low pitch, for instance) of one of three acoustic dimensions (fundamental frequency, waveform, or formant frequency) in brief-duration complex auditory signals. A complete description of these dimensions will be

presented below.

The analysis of auditory information processing, as visual processing, has typically followed a classical multi-stage model (cf., Lindsay & Norman, 1972; Neisser, 1967). Although the details of such models vary from author to author, in general, four major stages are identified: detection, feature extraction, recognition, and response. Each stage or sublevel represents a series of mental processes which share common characteristics. According to this model, in the first or detection stage the stimulus is encoded or converted to an internal representation. Frequently, this stage is associated with a sensory store or memory where information in its literal form is held briefly for later processing. The second or feature extraction stage, is considered to be the level at which the raw representation of the stimulus is broken down into its major features. This process is referred to as feature extraction. A square wave, for instance, is analyzed in terms of its loudness and pitch which in turn may be based on the relations among various harmonics.

The third level of processing, or the recognition stage, is of special relevance to memory since it is at this stage that the interaction of raw stimuli and higher cognitive processes takes place. For instance, an incoming pattern might be compared with previously stored patterns according to a particular rule. The result of this comparison is the naming or categorization of the original pattern. The fourth and last stage, the response stage, involves a determination of the output. This final stage is of little interest to the present report and will not be discussed further.

From this general model it is apparent that auditory perception depends on the ability of a listener to extract featural information from the stimuli, transform this information into a meaningful form by referencing stored information, and finally to initiate some sort of response. Furthermore, it is

obvious that the psychological mechanism underlying pattern recognition is a dynamic one involving the interrelation of all four levels of processing.

Distinction Features of Auditory Stimuli

For the most part, the major emphasis in past studies of auditory perception has been on the perception of the major parameters of relatively simple acoustic waveforms. These include such elements as frequency, amplitude, phase, and harmonic content. Such studies count into the hundreds and have, consequently, provided psychoacousticians with a rich background of material for the analysis of more complex auditory patterns. Although it is clearly important to understand how such basic acoustic features are perceived, it is also important to make a distinction between simple auditory features such as pitch (frequency), loudness (amplitude) and duration, and more complex features such as tonal complexity. Gibson (1966) especially stressed this distinction: "Instead of simple pitch, the (auditory stimuli) vary in timbre or tone quality, in combinations of tone quality, in vowel quality, in approximations to noise, in noise quality and in changes of all these in time . . . ." It is obvious that the relations among features of naturally occurring auditory events are critical to their perception, and a more complete statement of the auditory recognition process can not be made without a consideration of the perceptual properties of these more complex physical events.

Several methods have been used to examine the relative importance of complex auditory features. One successful method of investigating the degree of feature importance or saliency involves the application of a scaling technique such as the INDSCAL multidimensional scaling (MDS) method (Carroll & Chang, 1970). Such a method has been employed for speech sounds (Shepard, 1972), musical sounds (Miller & Carterette, 1975; Grey, 1977), and most recently, was employed in the

analysis of sonar (Howard, 1977) and sonar-like sounds (Howard & Silverman, 1976). In this latter study, the MDS technique was used to derive a relation between certain physical characteristics of complex non-speech sounds and their perceptual correlates. The MDS technique was found to be a successful method of determining which of the physical characteristics of a complex sound are perceptually important.

For the 16 sounds investigated by Howard and Silverman, three auditory features were found to differ in featural saliency: fundamental frequency, waveform, and the number and center frequency of formants. That is, in judging the similarity or difference between complex tones comprised of these features, listeners tended to use the fundamental frequency to a greater degree than waveform and formant frequency. The present study investigates the perception of these three features in brief duration signals.

Feature Extraction in Brief-Duration Auditory Signals

Earlier work has shown that under conditions where an auditory stimulus is presented for only a brief duration, identification of the signal will require processing time that exceeds the duration of the stimulus itself (e.g., Massaro, 1975; Sparks, 1976). Massaro (1975) has argued that a preperceptual auditory image or memory persists beyond the stimulus presentation which " . . . contains the necessary information for perceptual processing." The listener's auditory recognition processes are applied to the preperceptual image, extracting information about the auditory features present in the memory. Two experimental procedures have been used to examine memory for non-speech sounds: a paired comparison task and a recognition interference task.

In paired-comparison tasks, a standard and a comparison tone are compared. Typically, an increase in the inter-stimulus interval (ISI) between the tones

results in a decline in performance (Harris, 1952; Bachem, 1954). This has been attributed to a decay of the auditory image of the standard tone. Under conditions of variable intervals between the standard and comparison tone, performance can be degraded by events occurring between the standard and comparison tones. Wickelgren (1966) examined this effect by varying not only tone and ISI duration, but the duration of an interpolated interfering tone as well. In general, he found that a) the longer the duration of an interfering tone, the poorer the memory for the pitch of the standard, b) increasing the duration of the standard tone from two to eight seconds facilitated the memory for pitch and c) there were substantial differences in listener's performance with different types of auditory stimuli. Especially important to the present study is Wickelgren's suggestion that recognition performance is not only related to the duration of the stimulus and interference tones themselves but also depends on the interfering material. These findings have been supported in recent studies by Watson, Wroton, Kelly and Benbassat (1975) and Sparks (1976).

Deutsch, in a series of studies (1972a, 1972b), further examined this interactive effect for pitch memory. In general, her results indicated that memory for the standard and comparison tones can be disrupted or enhanced depending on the pitch of intervening tones. The two tones presented were to be compared for pitch. Six tones were presented within a five second interval between the standard and comparison tones. When the second tone of the sequence was identical to the standard, memory of the standard was facilitated. As the second interpolated tone changed in pitch (in increasing 5 Hz steps) memory for the standard decreased. In general, identification performance in a paired-comparison task will be influenced by the duration of the stimuli, the separation in time between stimuli, and by auditory events occurring between the tones.

In recognition interference studies a tone is presented to an observer for a few milliseconds. Under these conditions, a click-like sound will be heard. If the same tone is presented for a longer duration (greater than 10 msec), the tone will begin to acquire a pitch quality. In general, when asked to report the pitch of the tone, an observer's accuracy increases as the duration of the tone increases (Massaro, 1975). For longer tones more information is available for determining the pitch of the stimulus. In addition, if an observer is asked to report the pitch of a constant duration tone followed after a variable interval by a masking sound, accuracy will increase as the time between tone offset and noise onset increases.

Massaro has been particularly interested in the nature of the auditory image created by a tone. He suggests that a "temporal unit of an auditory stimulus is stored in a preperceptual auditory store" for later processing. This is very much like the visual image that persists after the offset of a visual stimulus (cf., Sperling, 1960; Averbach & Coriell, 1961; Neisser, 1967). In both modalities, perceptual processing depends on a preperceptual image where information is held for subsequent processing. Most important is the fact that the readout process takes a certain amount of time emphasizing "the temporal course of perceptual processing." Massaro's basic argument for a preperceptual store is that features (of an auditory image) cannot be recognized as they arrive since this requires that perception be immediate" (1972). He provides strong evidence for the existence of an image that outlasts a stimulus by manipulating the events following stimulus offset.

Observers in one of Massaro's experiments were trained to identify the particular quality of the stimuli. For instance, a tone might be of a "sharp" nature (square wave) or have a "dull" quality (sine); its pitch might be high (high frequency) or low (low frequency). Massaro reported that during testing,

recognition performance improved with increases in the silent ISI up to 250 msec. Recognition performance did not improve beyond this interval. In general, the poor performance after short ISIs was thought to reflect the termination of perceptual processing of the auditory image by the masking tone. Massaro and others (Elliot, 1967; Homick, Elfner, & Bothe, 1969; Efron, 1970) have examined these results further in forward masking designs as well as under conditions requiring the listener to estimate the duration of a test tone (since short tones produce an auditory image, listeners tend to overestimate their duration).

Summary

To summarize, the previous discussion has emphasized three major aspects of auditory information processing. First, the recognition of all auditory patterns, whether speech or non-speech, is based on their important auditory features. This is true for simple stimuli, such as pure tones, as well as for more complex patterns. Second, since time is required to process this information, the sounds must be maintained in some form of preperceptual memory. Third, it is convenient to consider auditory perception as the result of an ordered flow of information through specialized elements of a processing system. Finally, it is important to consider the processing of any auditory event as the product of a dynamic interdependence among a variety of processes.

At present, little research has considered how the recognition of a complex, brief-duration, non-speech sound depends on the particular dimensions or features present in that signal. Much of the evidence presented thus far suggests that listeners are differentially sensitive to particular acoustic information. Sensitivity, in the present usage, refers to the ability of a listener to classify a tone presented for a very short duration and followed by an interfering burst of white noise. Those auditory features that are more important or salient should be less effected by the white noise (regardless

of its temporal proximity) than those that are less salient.

The present study is designed to investigate the relative importance of different auditory features in a procedure similar to that of Massaro. However, unlike Massaro, the present research focuses primarily on the relation of performance to the featural composition of the auditory stimuli. More specifically, the primary question asked is: if a particular signal is composed of some combination of two possible frequencies, waveforms (e.g., triangle or square), and has different concentrations of acoustic energy (formants), which of these features "stand out" or lend themselves to clearer identification over others? If the listener is allowed to extract the important information from a stimulus under conditions where the amount of time allowed for this process is constrained, the relative perceptual importance of particular features should be reflected in the overall performance. The recognition interference task employed in the present study will not only provide information about the relative importance of specific auditory features, but will also permit inferences about the temporal course of the feature extraction process.

EXPERIMENT 1

Experiment 1 examines the effect of a masking noise on the classification of brief-duration auditory signals varying in either fundamental frequency, waveform or formant frequency. Each observer was asked to classify the signals into one of two categories (e.g., high or low) on the basis of each of the three features on different days. Since performance data are available for each observer on each feature, classification performance can be compared for difference features.

I. Method

A. Observers

The listeners were four female and four male students (aged 19-29 years).

All but one of the students attended The Catholic University of America. All reported having normal hearing; four listeners were randomly chosen and administered audiograms. Each observer was paid $18.00 to participate in three two-hour sessions.

B. Stimuli

As in the Howard and Silverman (1976) study, the stimuli were generated by driving a laboratory-constructed formant filter (Graeme, 1971) with a square or triangular wave at either 90 Hz or 140 Hz. The center frequency of the formant filter had a maximum amplitude 10 dB greater than the filter's response at 100 Hz. The stimuli were recorded continuously on magnetic tape for later playback during the experiment. Table 1 displays an outline of the three auditory features employed in the present experiment. The following notation was developed to describe the varying stimulus parameters:

$$\underline{S} = (\underline{F}_i, \underline{W}_j, \underline{f}_k)$$

where,

$\underline{S}$ = Stimulus

$\underline{F}$ = Fundamental frequency

$\underline{W}$ = Waveform

$\underline{f}$ = Formant frequency.

Fundamental frequency was either high ($\underline{F}_h$) or low ($\underline{F}_l$), waveform was either triangular ($\underline{W}_t$) or square ($\underline{W}_s$), and formant frequency either high ($\underline{f}_h$) or low ($\underline{f}_l$). Stimuli were equated for loudness for each listener using the method of constant stimuli in a pilot study.

C. Apparatus

All laboratory events were under digital computer control (PDP-8/E). Figure 1 displays a diagram of the instrumentation. All signals were played continuously on a 4-track stereo tape deck (TEAC 3300) into one of two picoreed

Table 1

Summary of the Three Auditory Stimuli Employed in Experiment 1

(the notation is described in the text)

OBS	WAVEFORM	FUNDAMENTAL FREQUENCY	FORMANT FREQUENCY
1	$S_1 = (F_h, W_s, f_h)$	$S_9 = (F_h, W_s, f_h)$	$S_{17} = (F_h, W_s, f_h)$
2	$S_2 = (F_h, W_t, f_h)$	$S_{10} = (F_l, W_s, f_h)$	$S_{18} = (F_h, W_s, f_l)$
3	$S_3 = (F_l, W_s, f_h)$	$S_{11} = (F_h, W_s, f_l)$	$S_{19} = (F_h, W_t, f_h)$
4	$S_4 = (F_l, W_t, f_h)$	$S_{12} = (F_l, W_s, f_l)$	$S_{20} = (F_h, W_t, f_l)$
5	$S_5 = (F_h, W_s, f_l)$	$S_{13} = (F_h, W_t, f_h)$	$S_{21} = (F_l, W_s, f_h)$
6	$S_6 = (F_h, W_t, f_l)$	$S_{14} = (F_l, W_t, f_h)$	$S_{22} = (F_l, W_s, f_l)$
7	$S_7 = (F_l, W_s, f_l)$	$S_{15} = (F_h, W_t, f_l)$	$S_{23} = (F_l, W_t, f_h)$
8	$S_8 = (F_l, W_t, f_l)$	$S_{16} = (F_l, W_t, f_l)$	$S_{24} = (F_l, W_t, f_l)$

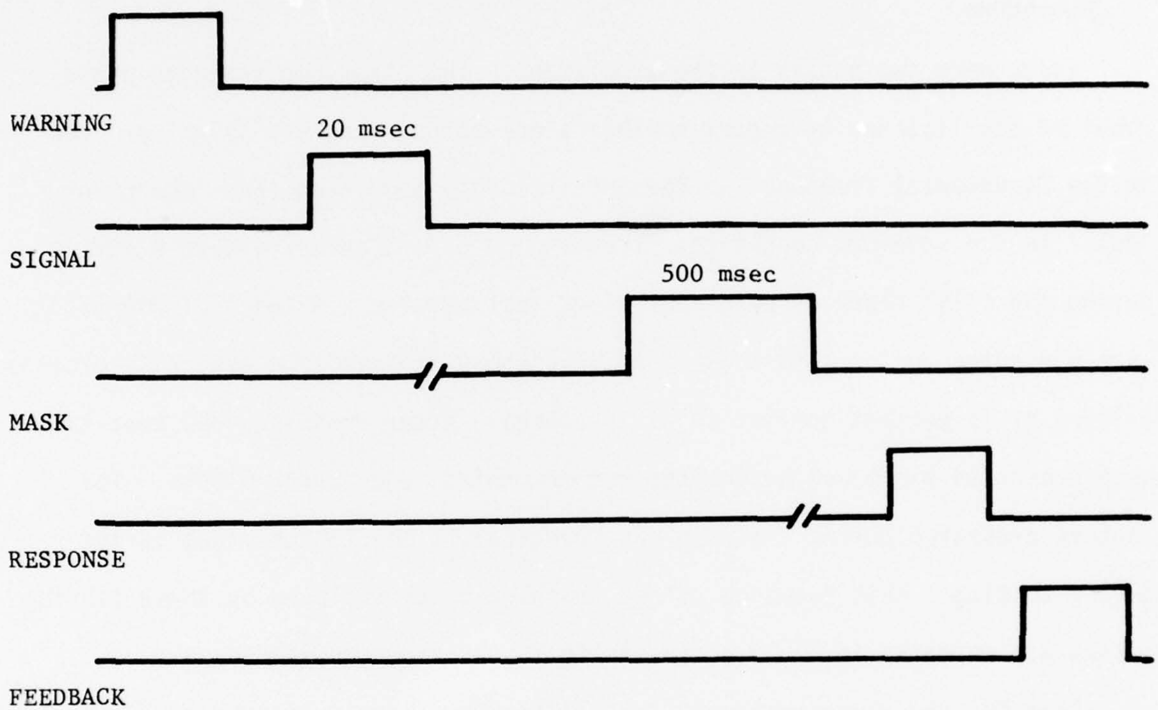

Figure 2. Timing sequence for a single trial on a backward masking recognition task.

relays. The broadband white noise (20 Hz - 20 kHz) was generated by a B & K model 1402 Randon Noise Generator. A third relay presented the noise. The tones and interfering noise were presented over matched Telephonics TDH-49 headphones at 83 dB SPL.

D. Procedure

There were two phases to the experiment. The first, or training phase, required the listener to report whether a one-second tone was "high" or "low" in the fundamental frequency or formant frequency condition, and "sharp" or "dull" in the waveform condition. Training on a particular feature occurred during the first block of each four-block test session. A total of 300 trials were presented during this phase. All listeners achieved and generally exceeded a level of 75 percent correct on all features. After training, 350 test trials were presented per block during the second, third, and fourth blocks. The feature presented during training was identical to the feature that varied during testing. This sequence of one training block followed by three testing blocks was repeated for each of the three features on separate days.

Signals were counterbalanced for all features across listeners. For example, consider fundamental frequency as displayed in Table 1. Observers were presented stimuli counterbalanced for waveform and formant frequency. Two of the listeners (#1 and #2) were presented tones generated by driving the formant filter centered at 940 Hz by a 90 Hz or 140 Hz square wave. Listeners 3 and 4 were presented tones generated by driving the formant filter centered at 600 Hz by a 90 Hz or 140 Hz square wave. Listeners 5 through 8 received similar counterbalancing with triangular wave signals. The waveform and formant frequency conditions were counterbalanced in a similar manner. The sequence of treatment presentation was randomized over listeners.

On each trial a complex signal was presented for 20 msec followed, after

a variable ISI (0, 40, 80, 160, 250, 350, 500 msec), by a 500 msec white noise burst. The listener reported whether the tone was high or low (sharp or dull). Feedback was given on all trials. Figure 2 presents a diagram of the sequence of events for one experimental trial. In all conditions a single feature was varied while the other features remained constant. The ISI as well as the levels within each dimension were presented randomly during each session, with the only constraint that an equal number of trials occurred for all ISIs and levels.

Each experimental block consisted of 350 trials (25 trials/feature x 7 ISIs x 2 levels). An average trial took 4.5 seconds. There were three 25 minute blocks of trials with a 10-minute rest period between blocks.

II. Results

Recognition performance was recorded for all listeners for each ISI and feature. Percent correct scores were converted to levels of d' with the use of the Elliot table presented in Swets (1964). A discussion of the rationale for applying the theory of signal detection to a recognition memory paradigm can be found in Egan (1958). A preliminary analysis of the performance data revealed no overall listener bias to report "high" or "low," but nonetheless, bias-free d' scores were employed. Figure 3 presents d' levels for each ISI and feature averaged across the eight listeners.

Massaro has outlined a formal theory where the discriminability level, d', can be described by an exponential function of time as in equation (1):

$$d' = \alpha (1 - e^{-\theta t}) \quad (1)$$

where,

α = the asympotic level of d'

θ = a rate parameter reflecting the rate at which the asymptote is approached

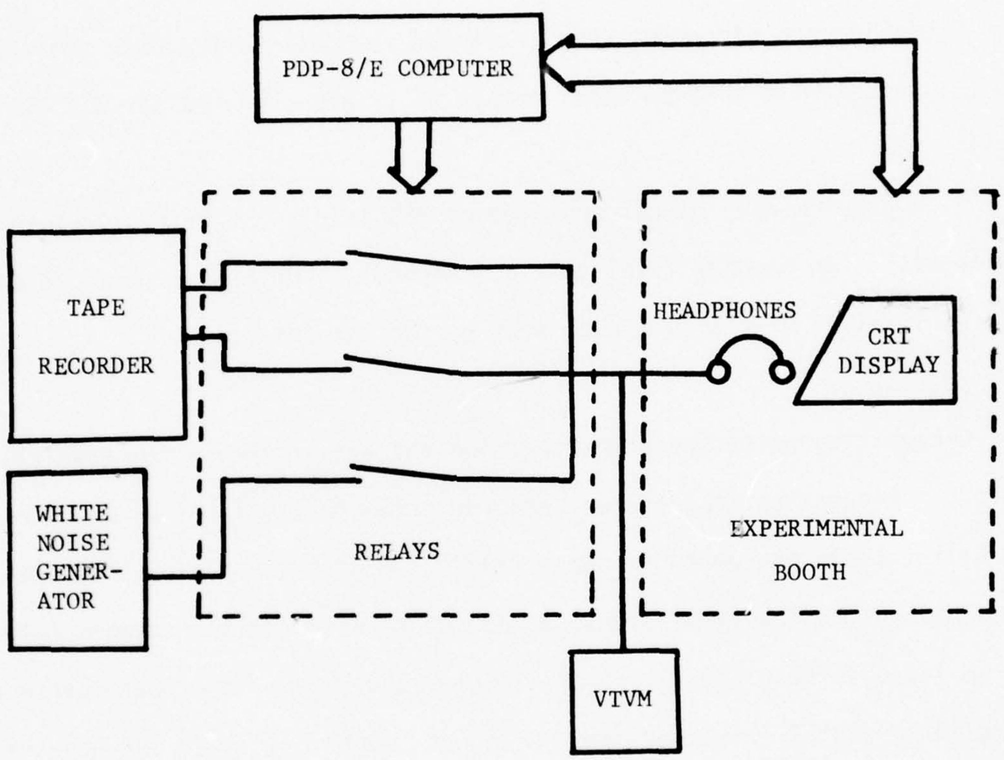

Figure 1. Signal generation and response acquisition configuration.

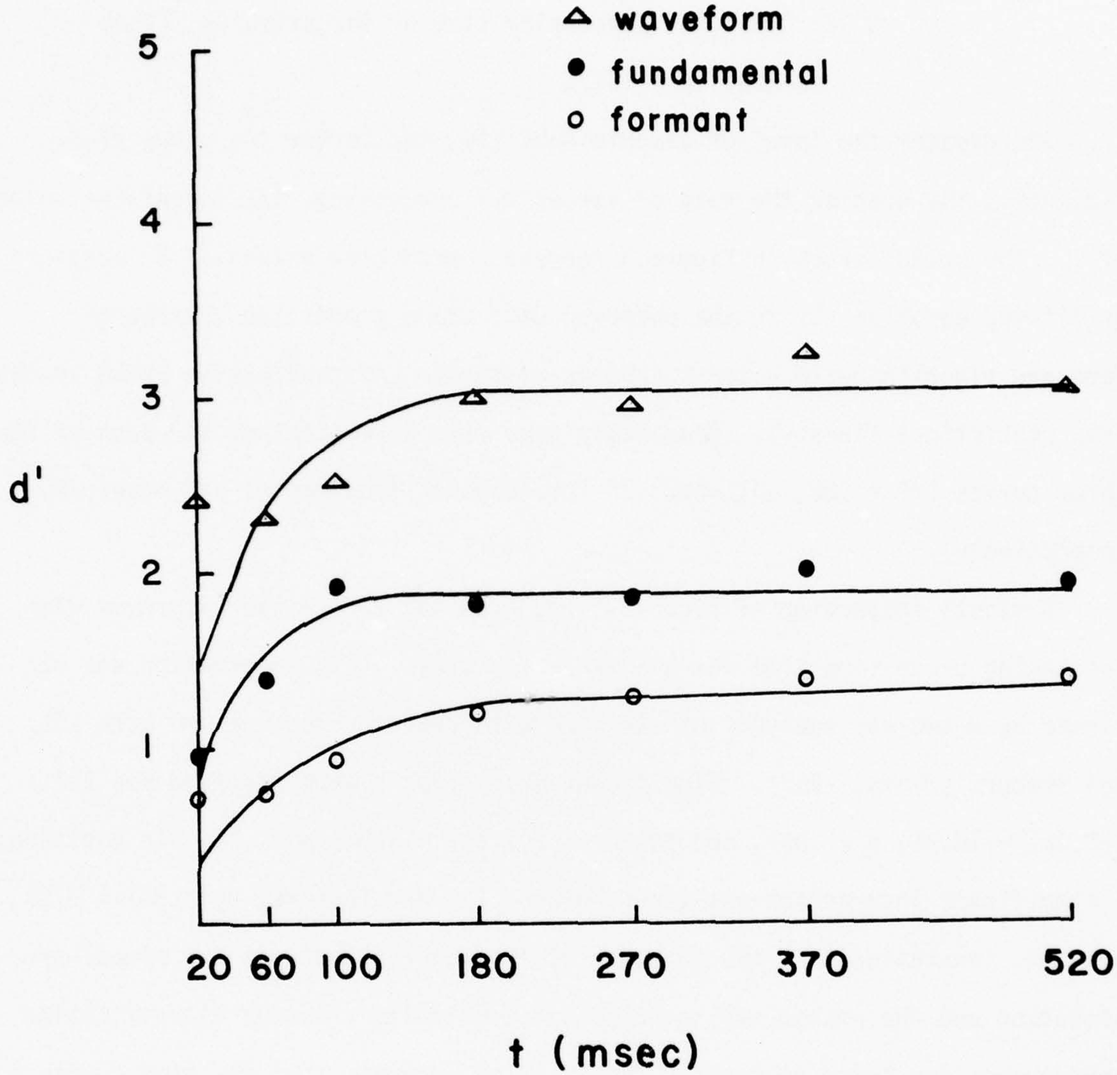

Figure 3. Sensitivity for waveform, fundamental frequency, and formant frequency as a function of total processing time, t. Solid lines are predicted values given by equation [1].

t = the total processing time of the stimulus, (tone duration + ISI).

The greater the level of discriminability, the larger the value of α. Similarly, the greater the rate of perceptual processing, the larger the value of θ. The solid curves in Figure 3 represent predicted values of d' obtained by fitting equation (1) to the observed data using a modified Levenberg-Marquard algorithm with a least squares criterion (cf. subroutine ZXSSQ in the IMSL statistical library). Reasonably good fits were obtained for each of the three curves (r^2 = .82, .91, and .93 for formant, fundamental and waveform, respectively).

A visual inspection of Figure 3 suggests that recognition improved with increasing processing time for all three features. This observation was confirmed by a two-way analysis of variance with repeated measures on both ISI and feature (Myers, 1967). Significant main effects were observed for ISI, $F(6,42) = 18.98$, $p < .001$, and Feature, $F(2,14) = 6.55$, $p < .01$. In addition, a significant interaction was found between ISI and Feature, $F(12,84) = 3.37$, $p < .01$, indicating that the duration of the interval between the signal presentation and the masking white noise differentially affected classification performance for three features. This finding suggests that the time course of the feature extraction process involved in the recognition interference task depends on the auditory dimension or feature being analyzed.

A further analysis of mean d' levels over sessions (t tests) revealed no significant difference between any two sessions. This result, and the fact that no practice effects were found with training, indicates that learning effects were absent during the test phase of the experiment.

As previously described, an elaborate counterbalancing procedure was employed for each auditory feature. For instance, stimuli varying on the

waveform dimension were counterbalanced for fundamental frequency and formant center frequency. Consequently, four combinations of stimuli varying on waveform were possible, and two listeners were presented with each particular combination. To insure that there were no differences in d' scores associated with stimuli over all counterbalanced features, comparisons were made between mean performance (collapsed over ISI) of listeners in each group. No significant differences were found.

III. Discussion

Two major conclusions are evident from the present experiment. First, the noise was effective in disrupting processing of the auditory image created by a short burst of a complex auditory signal. As in Massaro's earlier studies (1970; 1975), performance reached an asymptotic level at an ISI between 160 and 250 msec. This suggests that the duration of the auditory image for complex non-speech sounds is approximately 200 msec, generally consistent with estimates from recognition interference studies employing both simple non-speech (Massaro, 1975) and speech (Wolf, 1976) signals.

Second, accurate identification of a complex signal depends critically on its psychophysical structure. Differential performance on the three auditory features was revealed in both the rate of information processing (as indicated by the different shaped performance by ISI functions for the three features), and in the maximum performance reached (as indicated by the different asymptotes for the three features). This suggests that either: (a) different feature extraction processes are involved in the analysis of the three different features, or (b) the same feature extraction process proceeds at different rates and to different levels for different features.

In order to further explore the acoustic correlates of performance in the present task, the physical structure of the signals was examined for possible

correlates with classification performance. Each of the signals was subjected to a narrow-band spectral analysis using a Federal Scientific Spectral Analyzer, Model UA-100. Figure 4 presents the steady-state line spectra for two examples of each of the three features. The spectra have been ordered with the most easily discriminable pair on the top to the least easily discriminable on the bottom. Before progressing further, it should be noted that the spectra presented in Figure 4 were obtained from steady-state signals rather than from the 20 msec bursts used in the experiment. As Licklider (1951) has pointed out, the spectrum of a brief-duration signal will be distorted or "smeared" relative to its steady-state spectrum. Nonetheless, the spectra presented in Figure 4 should be useful in clarifying the psychoacoustic basis of performance in the present task. Instances where the spectral smearing is likely to have influenced performance will be noted below where appropriate.

As is evident in Figure 4, the principal difference between the two waveforms lies in the distribution of harmonics. While both the square (Figure 4a) and triangular (Figure 4b) waves are composed of only odd harmonics, the distribution is much more steeply sloped for the triangular wave. At the intensity levels investigated in the present study, more harmonics would be audible for the square than triangular waves. The net result is that the partials present in the square wave influence more critical bands than those present in the triangular wave [below approximately 1 kHz, the critical bands are roughly ± 50 Hz about the center frequency (Scharf, 1971)]. In the frequency condition (Figures 4c and 4d), the only physical difference is in the spacing between harmonics. That is, the harmonics of the 90 Hz fundamental (Figure 4c) are more closely spaced than those of the 140 Hz fundamental (Figure 4d).

For formant frequency, the only physical difference lies in the amplitude relations among all the harmonics. For example, in Figure 4e, a 90 Hz square

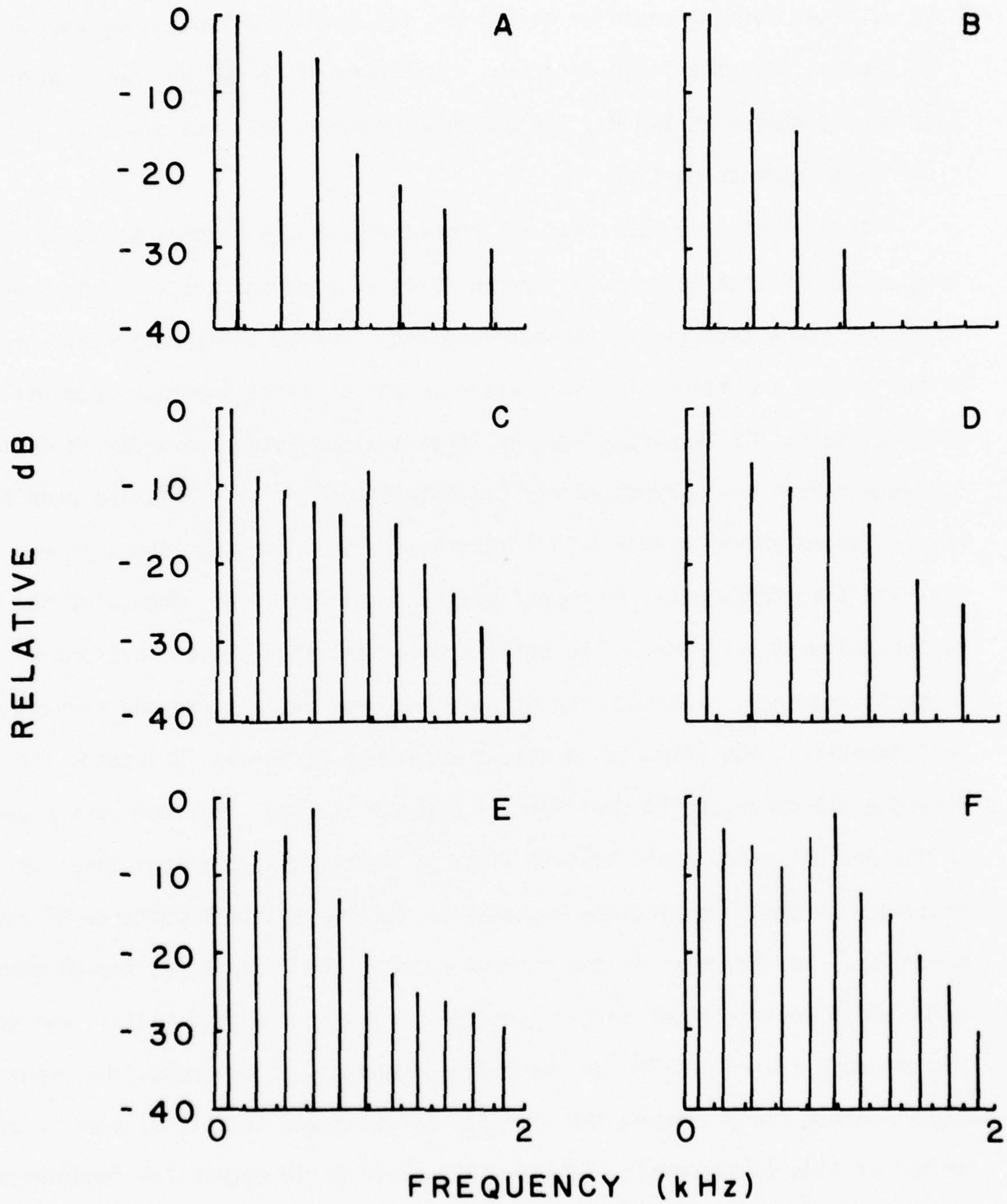

Figure 4. Steady-state line spectra for signals differing in waveform (a & b), fundamental frequency (c & d), and formant frequency (e & f).

wave with the formant centered at 600 Hz, the seventh harmonic was approximately 4 dB greater than the fifth or ninth. In Figure 4f, a 90 Hz square wave with a formant centered at 940 Hz, the eleventh harmonic was 4 dB greater than the ninth or thirteenth partial.

This analysis suggests that the number of audible harmonics (i.e., waveform), the distance between the harmonics (i.e., fundamental), and the amplitude relations among them (i.e., formant frequency) occupy a respective hierarchy of subjective importance in the classification of brief-duration segments of these signals. It is clear, however, that the suggested hierarchy of featural salience cannot be absolute or rigidly determined for all listening conditions. In the Howard and Silverman (1976) multidimentional scaling study, it was revealed that fundamental frequency was more salient (i.e., accounted for more of the judgment variance in the scaling solution) than either waveform or formant frequency. Although the stimuli employed in this and the present study were identical, the stimulus durations were very different (3 seconds for Howard & Silverman and 20 msec for the present study). The tone bursts used in the present study would tend to preserve relatively more high than low frequency information, thereby emphasizing the subjective importance of the harmonics. For example, in the extreme case of the 90 Hz tone, the 20 msec burst would contain fewer than 2 complete cycles at the fundamental, but would contain more than 10 cycles at the fifth harmonic. In contrast, the Howard and Silverman study allowed the listener to integrate the signal over a longer period of time (3 seconds), enabling that observer to stress the fundamental--the frequency containing the greatest relative energy.

Implicit in the above analysis is the assumption that the three auditory features (fundamental frequency, waveform and formant frequency) are revealed

or extracted from a complex sound by three different feature extraction processes. However, as pointed out above, an equally viable alternative is that the three features differ only along the single dimension of discriminability, and therefore differentially influence a single feature extraction process. According to the latter hypothesis, the three features examined in the present study lead to different sensitivity by ISI functions primarily because the specific feature values investigated were not equated for discriminability. For example, it is conceivable that the psychological processes responsible for distinguishing two square waves that differ by 10 Hz are no different from those responsible for distinguishing sounds having two distinctive formants but identical fundamentals. Since no previous recognition interference studies have investigated the effects of discriminability on classification performance, the effects of this variable and its role in determining featural saliency remain unclear. Experiments 2 and 3 are designed to examine the effects of discriminability on recognition performance for two auditory features (formant frequency and fundamental frequency, respectively).

EXPERIMENT 2

In this experiment, formant frequency is varied along a single continuum of discriminability by changing the separation between the center frequencies of the formants in 90 Hz square waves. Listeners are required to classify signals into two categories on the basis of formant frequency under three conditions. The three conditions investigated the original formant center frequency difference of 600/940, a more discriminable difference of 600/1000, and a still greater difference of 600/1200. If recognition performance varies with discriminability in a manner identical to that observed in Experiment 1 (i.e., different asymptotes and rates for the three levels), then this would suggest

that the results of Experiment 1 could be attributed to discriminability differences and not to any unique psychological characteristics of the different features. If, on the other hand, recognition performance in the present study differs from that of Experiment 1 (e.g., asymptotes, but not rates, differ for the three levels), then this would provide evidence that the three features are extracted by distinct psychological processes.

I. Method

A. Observers

Two male and two female undergraduates, aged 19-22 years, served as observers. No participant had participated in the first experiment or had any known history of hearing disorders. Instructions and payment were identical to those of Experiment 1.

B. Apparatus

The apparatus was identical to that of Experiment 1. Three stimulus tapes were generated by passing a 90 Hz square wave through the previously described formant filter centered at one of the four different frequencies. One tape was recorded with the formant frequency centered at 600 Hz on one channel and 1000 Hz on the other. A second tape was similarly recorded with the formant frequencies centered at 600 and 1200 Hz. A formant tape recorded for the first experiment (center frequencies at 600 and 940 Hz) was used for the third stimulus pair. All stimuli were presented at a listening level of 83 dB SPL.

II. Results

Figure 5 presents the d' levels averaged over all four listeners. For all levels of formant discriminability, recognition performance improved with increasing ISI. These data were analyzed with a two-way repeated measures analysis of variance. As suggested by visual inspection of Figure 5, main effects were

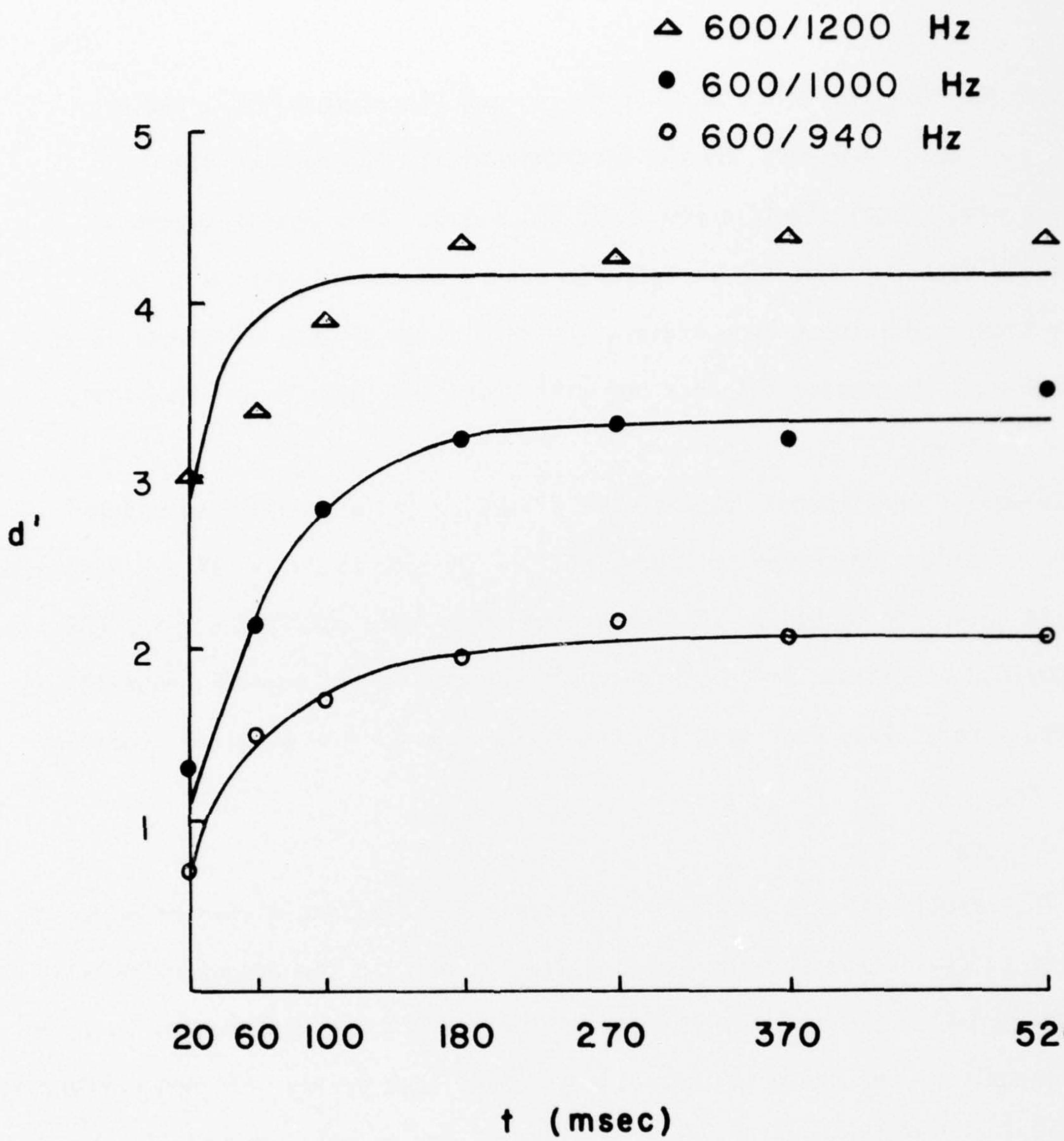

Figure 5. Sensitivity for three levels of formant frequency discriminability as a function of total processing time, t. Solid lines are predicted values given by equation [1].

observed for ISI, $\underline{F}(6,18) = 14.40$, $\underline{p} < .01$, and Discriminability, $\underline{F}(2,6) = 26.72$, $\underline{p} < .001$. However, the ISI Discriminability interaction did not approach statistical significance, $\underline{F}(12,36) < 1.0$. This result suggests that while higher asymptotic performance occurs for sound pairs with more widely separated formant frequencies, the rate at which this asymptote is approached with increasing ISI does not differ for the three discriminability levels examined.

Curves of predicted d' values were fitted to the data using equation 1 and the procedure described in Experiment 1. The predicted values are displayed as solid curves in Figure 5. Extremely good fits were obtained for the 600/940, and 600/1000 conditions ($r^2 = .99$ and $.97$, respectively); however, equation 1 provided a relatively poor description of the data for the 600/1200 condition ($r^2 = .62$).

III. Discussion

The results of this experiment are clear in revealing different asymptotic performance levels for stimulus pairs differing only in the frequency separation between formants. This finding indicates that asymptotic performance is determined largely by feature discriminability rather than by any inherent perceptual characteristic of the auditory feature itself. For example, asymptotic performance for the 600/1200 condition in the present experiment ($\alpha = 4.16$) far exceeded that observed for the waveform condition of Experiment 1 ($\alpha = 3.05$). This occurred despite the fact that in Experiment 1 the formant condition produced the lowest asymptote ($\alpha = 1.34$).

The present findings also suggest that similar processing rates occur for stimuli differing only in discriminability along a single auditory feature. Although this result is not immediately obvious from a visual inspection of

Figure 5, a statistical analysis of the data was clear in revealing no significant ISI Discriminability interaction. This finding contrasts with the highly significant interaction observed in Experiment 1 where feature was varied.

EXPERIMENT 3

Experiment 3 is designed to extend the findings of Experiment 2 to a second auditory feature, fundamental frequency. Observers were required to categorize brief-duration complex sounds as "high" or "low" on the basis of their fundamental frequency. As in Experiment 2, three sound pairs of varying discriminability were employed and each signal presentation was followed by an interfering white noise burst. If the effects of discriminability noted in Experiment 2 apply to recognition performance of features other than formant frequency, then similar effects should be observed in the present study.

I. Method

A. Observers

Two male and two female observers participated in the experiment. No participant had served in either of the previous experiments or reported any known history of hearing disorders. Instructions and payments were identical to those of Experiment 1.

B. Apparatus

The apparatus was identical to that of Experiment 1. Stimulus tapes were generated by recording a square wave of 90, 120, 130 or 140 Hz fundamental through the formant filter centered at 600 Hz. Three test pairs of 90/120, 90/130, and 90/140 Hz were produced to obtain three levels of discriminability. The signals were subjectively equated for loudness before being presented at a comfortable listening level (83 dB SPL).

II. Results

Mean d' values, averaged across the four observers, are displayed in Figure 6. As in both earlier experiments, performance improved with increasing ISI up to an asymptote at approximately 200 msec, $\underline{F}(6,18) = 8.70$, $\underline{p} < .001$. In addition, as in Experiment 2, higher asymptotic performance was observed for the more widely separated signal pairs, $\underline{F}(2,6) = 9.87$, $\underline{p} < .025$, but no reliable differences were observed in the rate at which performance approached this asymptote with increasing ISI, $\underline{F}(12,36) = 1.43$, $\underline{p} > .10$.

Predicted d' values, displayed in the solid curves of Figure 6, were fitted to the data as described above. However, in contrast to the earlier experiments, relatively poor fits were obtained for all three conditions (r^2 = .53, .80, and .62 for the 90/120, 90/130, and 90/140 conditions, respectively). Visual inspection of Figure 6 suggests that the worst fits are observed at the shortest ISIs. This observation was confirmed in a closer examination of the data which revealed substantially larger mean squared deviations from the predicted values for the first three ISIs (deviations of .079, .071, and .170 for the 90/120, 90/130, and 90/140 conditions, respectively) than for the last four (deviations of .022, .065, and .024, respectively). In short, it appears that equation 1 does not provide an adequate description of the present data for short ISIs.

III. Discussion

In general, the results of this experiment are consistent with those reported for formant frequency in Experiment 2. Once again, discriminability had a large effect on asymptotic performance with more widely separated stimulus pairs showing correspondingly higher asymptotes. In addition, asymptotic performance levels for all three discriminations investigated in the present study

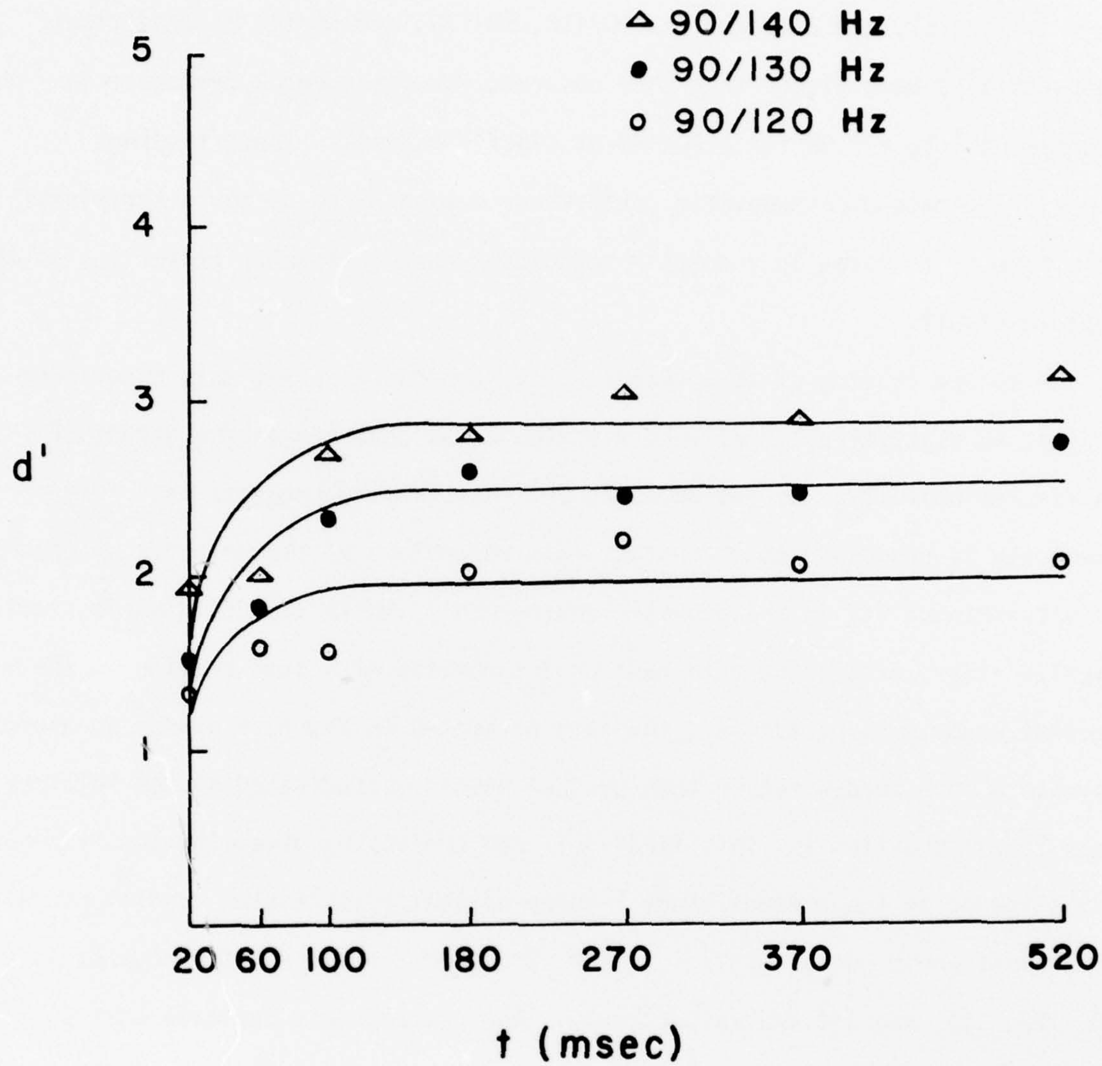

Figure 6. Sensitivity for three levels of fundamental frequency discriminability as a function of total processing time, t. Solid lines are predicted values given by equation [1].

(α = 1.97, 2.51, and 2.86 for the 90/120, 90/130, and 90/140 Hz conditions, respectively) were higher than that observed for fundamental frequency in Experiment 1 (α = 1.92 for a 90/140 Hz discrimination). These findings clearly indicate that asymptotic performance depends more on the discriminability of critical features in a complex sound than on any singular properties of the feature itself.

A second finding of the present study, again consistent with Experiment 2, is that no statistically reliable difference was observed in the effect of ISI on discriminability. As indicated above, this finding suggests that fundamental frequency is processed at a constant rate regardless of its relative salience or discriminability in the acoustic environment. While this finding is statistically clear, processing rate must be interpreted with some caution in the present study. In particular, the data presented in Figure 6 appear to approach asymptote in a sudden rather than gradual manner as indicated by the relatively poor fit of equation 1. This finding is not surprising given the low frequencies investigated in the present study. Under optimal presentation conditions, a 20 msec burst would contain only 1.8, 2.4, 2.6, and 2.8 cycles at fundamentals of 90, 120, 130, and 140 Hz, respectively. The present data indicate that a minimum processing time of between 100 and 180 msec is required to extract sufficient information from the auditory image to make this discrimination.

GENERAL DISCUSSION

The present study examined the sensitivity of listeners to three selected auditory features in a two-choice, recognition interference task. Two major findings are evident. First, asymptotic recognition performance in this task depends on a variety of stimulus as well as subjective factors. However, there is little evidence in the present study to indicate that featural saliency, as

reflected by asymptotic performance, is determined by any unique perceptual property of individual features. Second, the results suggest that different auditory features are processed at different rates, but that processing rate remains invariant when discriminability is varied with feature held constant. These major findings are discussed in more detail below.

Asymptotic Performance

Listeners in the present study were clearly able to selectively respond to specific auditory features in brief-duration, complex non-speech sounds. Experiment 1 revealed substantial differences in the performance asymptotes for three different auditory features (waveform, fundamental frequency, and formant frequency). A comparison of these findings with the results of Experiments 2 and 3, suggest that at least two stimulus parameters are important in determining asymptotic performance level: signal duration and stimulus discriminability.

The importance of signal duration became evident in a comparison of the results of Experiment 1 and the earlier scaling study. In Experiment 1, waveform produced the highest asymptote with fundamental and formant yielding successively lower overall performance levels. On the other hand, in the scaling study, fundamental frequency accounted for substantially more of the total judgment variance than did waveform. Although the signals were identical in the two studies, two major differences may be noted: (1) the responses required were quite different, and (2) dramatically different signal durations were used in the two studies. In Experiment 1, listeners categorized brief presentations (20 msec) of individual sounds, whereas in the scaling study, listeners were required to make relative similarity judgments of successively presented three-second segments of two sounds. Although it is impossible to

rule out the possibility that listeners use different criteria in making classification responses and similarity judgments, it is more likely that signal duration was the key factor underlying the different pattern of results observed in these studies. As was indicated above, the tone bursts used in Experiment 1 would tend to preserve relatively more high than low frequency information, and hence, the subjective importance of waveform would be enhanced relative to fundamental. On the other hand, when listeners had a sufficiently long integration period, as in the scaling study, the low-frequency fundamental would become more important relative to waveform.

The second stimulus factor influencing asymptotic performance level is signal discriminability. Experiments 2 and 3 revealed higher asymptotic performance for signal pairs having larger physical differences. In both experiments where discriminability was varied, asymptotic performance equalled or exceeded that observed for the corresponding conditions in Experiment 1. The implication of these findings is that differences in asymptotic performance cannot be attributed to any invariant subjective property of individual auditory features. Rather, at least two physical characteristics of the stimulus, its duration and relative distinctiveness, have a major influence on a listener's ability to selectively respond to individual features in a complex non-speech sound.

In addition to these stimulus factors, at least one subjective factor--the amount of prior experience in classifying sounds on the basis of a particular feature--played a primary role in determining asymptotic performance in the present study. When absolute performance levels are compared for the corresponding conditions across the present experiments, it becomes evident that Experiments 2 and 3 produced substantially higher overall levels than did

Experiment 1. For example, in Experiment 2, where formant discriminability was varied, the asymptotes for all three discriminability levels (α = 2.06, 3.33, and 4.16) were higher than that observed for the formant condition in Experiment 1 (α = 1.34). Similarly, the three asymptotes observed when fundamental separation was varied in Experiment 3 (α = 1.97, 2.51, and 2.86) all exceeded the asymptote for the comparable condition in Experiment 1 (α = 1.92).

Since this discrepancy occurred even for identical signal pairs, the differences cannot be attributed to any physical characteristics of the auditory waveforms. Similarly, differences in the absolute amount of practice cannot account for these findings since listeners in all three experiments received the same number of trials. It should be noted, however, that while all listeners had an identical amount of overall experience in the task, listeners in Experiments 2 and 3 always classified signals on the basis of a specific feature, whereas the listeners in Experiment 1 classified stimuli on the basis of three different features on separate days. Hence, it appears that experience with a specific feature leads to substantially better performance than does experience with different features.

Two different psychological mechanisms could underlie this effect. First, observers may simply develop an improved ability to selectively focus their feature extraction efforts on a particular relevant feature, and ignore other irrelevant features. Similar improvements in selective attention have been reported for experienced listeners in discriminating temporally varying tonal patterns (Watson, Wroton, Kelly, & Benbassat, 1975). It should be noted, however, that if an improvement in attentional ability were occurring, the relative lack of improvement observed in Experiment 1 would suggest that such improvement would be quite feature specific.

Second, it is possible that the observed differences reflect an increased absolute sensitivity to the practiced feature. In other words, extended practice may improve the efficiency or accuracy of the feature extraction process itself. Although the present study was not designed to distinguish between these alternatives, it is clear that the performance levels observed in the present experiments--especially Experiment 1--do not reflect any absolute limit on a listener's ability to recognize specific features in brief-duration complex sounds. It remains for future research to empirically clarify the two possible psychological mechanisms outlined above.

Rate of Processing

One of the most obvious findings of the present study was that performance improved with increasing ISI. The longer the period between signal presentation and the interfering noise burst, the higher the performance level up to some optimal asymptotic value. As indicated above, this finding is consistent with Massaro's (1975) earlier data, and with his argument that brief-duration sounds are retained in a short-lived auditory memory for further processing. In Massaro's thinking, the time between the signal offset and noise onset is consumed by "primary recognition processes" which transform the relatively unprocessed auditory image into a categorical (i.e., recognized) representation. Since the interfering noise is thought to disrupt this and terminate this process, the rate of recognition processing is revealed in the rate at which performance improves with increasing ISI.

In Experiment 1 of the present study, ISI was observed to differentially influence performance for the three auditory features. In contrast, when feature was held constant while discriminability was varied in Experiments 2 and 3, no statistically reliable difference was noted in the effects of ISI on

performance. Since post asymptotic data in the three experiments were relatively stable, these results suggest that different auditory features are processed at different rates, but the rate of processing for a particular feature remains invariant when factors influencing asymptotic performance are varied. This would be expected if different feature extraction processes were applied in the analysis of the three features examined in the present study. Furthermore, this interpretation is also consistent with the previously discussed finding that extended practice selectively improves performance for particular features. However, despite its apparent theoretical consistency, this finding must be interpreted with caution for at least two reasons. First, the finding is based on a comparison of data across experiments using different listeners and different numbers of participants. Second, a comparison of processing rates across conditions assumes that performance improves in an orderly and systematic fashion as ISI is increased. In the present data, relatively large variance was observed at the short ISIs (i.e., 0, 40, 80 msec), and as indicated above, the data of Experiment 3 appear to show a sudden rather than gradual improvement with increasing ISI.

Implications

The present findings clearly indicate that the stimulus environment plays an important role in determining the subjective importance of auditory features. They suggest that selective changes in the auditory environment (e.g., through signal preprocessing) could significantly enhance a listener's ability to recognize even relatively subtle acoustic cues (e.g., formant frequency). The findings also suggest that practiced listeners may have an improved ability to selectively focus their attention on specific auditory cues in a complex aural display. It appears that extended practice with important, but initially

unsalient cues, would lead to a greater performance increment than would an equivalent amount of practice with a variety of cues. Overall, the backward recognition interference paradigm was shown to be a valuable tool for examining the effects of various signal parameters on an observer's ability to extract information from complex sounds. In addition, its potential for examining the time course of auditory information processing may prove invaluable.

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